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The Use of a Steering Shaping Function to Improve Human Performance in By-Wire Vehicles

by Susan G. Hill, Jason S. Metcalfe, and Kaleb McDowell

ARL-TR-4387 March 2008

TARDEC

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
March 2008

2. REPORT TYPE
Final

3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE
The Use of a Steering Shaping Function to Improve Human Performance in By-Wire Vehicles

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Susan G. Hill and Kaleb McDowell (both of ARL); Jason S. Metcalfe (DCS)

5d. PROJECT NUMBER
62716AH70

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Human Research and Engineering Directorate
Aberdeen Proving Ground, MD 21005-5425

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-4387

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
J.S. Metcalfe (DCS) participated in this collaborative effort as a result of a U.S. Army Tank-Automotive Research Development and Engineering Center (TARDEC)-sponsored project. This work is a collaborative effort between TARDEC and ARL.

14. ABSTRACT

The U.S. Army is examining evolutionary concepts for the command and control of military vehicles. Currently, there is a performance issue regarding vehicle control at higher speeds for some indirect vision, by-wire tactical vehicles. By-wire vehicles are those in which mechanical links between the driver and control devices are replaced by electronic or computerized signals. Specifically, an operator's ability to maintain reliable control of by-wire military vehicles while driving appears to be progressively compromised as vehicle speed increases. Several factors have been identified as possible sources of this difficulty, including lags in the system control loop, characteristics of the steering interface (such as its shaping function or lack of force feedback), inadequate visual display, and physical effects of vehicle motion on the operator (McDowell et al., 2007a). This report is a review of the current state of knowledge regarding the steering shaping function, which specifies the dynamic spatial relationship between steering input from the driver and vehicle heading direction. The overall goal of the review is to identify design parameters critical to improving current by-wire implementation in military tactical vehicles, thereby identifying design elements to optimize human-vehicle system performance for secure mobile operations.

Through a review of general automotive literature related to variable gear ratio steering systems as well as steer-by-wire design and implementation, three main factors affecting steering control were identified. The primary factors of influence that were reviewed included the overall range of motion ("throw") of the steering device, the steering shaping function, and modifications of the shaping function because of vehicle motion characteristics. In addition, variations in performance were observed to be a consequence of dynamic characteristics of the operator and the vehicle and most importantly, the interaction between the operator and the vehicle. This review concludes that the shaping function is a central influence over system performance, and further, it is apparent that no single shaping function will suffice across all driving scenarios. Owing to noteworthy driver performance issues at higher vehicle speeds (particularly with nonstandard steering devices, such as joysticks), a call is made for further research to extend the current understanding of steering control. Specifically, we suggest that the achievement of optimal steering characteristics will most likely come with a greater understanding of the dynamic variations needed within shaping functions in order to accommodate different vehicle, task, and operator characteristics.

15. SUBJECT TERMS
drive by wire; human performance; shaping function

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Susan G. Hill
Unclassified	Unclassified	Unclassified	SAR	35	19b. TELEPHONE NUMBER (*Include area code*) 410-278-6237

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Acknowledgments

This work is the result of a collaborative effort between the U.S. Army Tank-Automotive Research, Development, and Engineering Center (TARDEC) and the U.S. Army Research Laboratory. Specifically, the author Jason S. Metcalfe participated in this effort as a result of a TARDEC-sponsored project at DCS Corporation.

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1. Statement of Issue

The U.S. Army is examining evolutionary concepts for the command and control (C2) of military vehicles. Currently, there is an important performance issue regarding vehicle control at higher speeds for some indirect vision, by-wire vehicles, that is, those vehicles in which mechanical links between the driver and control devices are replaced by electronic or computerized signals. Specifically, an operator's ability to reliably maintain control of by-wire military vehicles during mobility appears progressively compromised as vehicle speed increases. Several factors have been identified as possible sources of this difficulty, including lags in the system control loop, steering shaping function and/or lack of force feedback, inadequate visual display, indirect vision system, and finally, physical effects of vehicle motion on the operator (McDowell, Oie, Tierney, & Flascher, 2007). This review is intended to assess the current state of knowledge regarding one of these factors, specifically, the shaping function. The overall goal is to support the identification of design parameters critical to improving the current by-wire implementation for military tactical vehicles and to ultimately optimize system (i.e., human-vehicle) performance for the execution of secure mobile operations.

2. Introduction

In support of future force initiatives, the U.S. Army is examining new and evolutionary concepts for modernization of the C2 of military vehicles. Advanced development of vehicle electronics (vetronics) technologies is seen as a catalyst, pushing the transformation of the U.S. military to a highly networked and automated presence on the battlefield (Keller, 2004). One program aimed at the development and implementation of advanced vetronics technology is the Crew Integration and Automation Test Bed (CAT; see figure 1), developed at the U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) in collaboration with the U.S. Army Research Laboratory's (ARL's) Human Research and Engineering Directorate. The CAT provides an important platform for conducting research on a variety of issues, among which are human factors considerations associated with staffing semi-autonomous and/or autonomous vehicles with a reduced crew of two military personnel. Of primary concern as research and development efforts proceed is the influence of automation and related technologies on the human-vehicle system performance during secure mobile operations, defined here as operations that require sustaining a real-time understanding of the environment local to one's vehicle and platoon (local area awareness) concurrent with the performance of primary tasks for terrain traversal (McDowell, Nunez, Hutchins, & Metcalfe, 2008).

Figure 1. The CAT, based on a modified Stryker vehicle, undergoing development at TARDEC in collaboration with ARL.

The optimization of Soldier performance during secure mobile operations is critical to the successful realization of future force concepts (McDowell et al., 2007). As the level of technology integrated into fielded equipment increases while crew sizes decrease, Soldiers are likely to be faced with elevated cognitive and physical workload during vehicle operation. The tasks associated with driving the vehicle, such as steering, throttle and brake control, appear as ideal candidates for the incorporation of automation for the purpose of increasing vehicle safety and security while reducing operator workload. However, several human performance issues arise from the incorporation of technical solutions for meeting automation needs in vehicle control systems (Andonian, Rauch, & Bhise, 2003; Stanton & Marsden, 1997; Stanton & Young, 1998). Thus, engineering decisions regarding the "what and how" of such implementations are made challenging in nontrivial ways. Included in the problems induced by the staffing of automated systems are biomechanical (Sirouspour & Salcudean, 2003; Sövényi & Gillespie, 2007), cognitive (Parasuraman & Riley, 1997), and psychomotor (Stanton & Marsden, 1997; Stanton & Young, 1998) issues affecting the execution of system control tasks.

The current review focuses on one specific aspect of these problems, that is, performance issues associated with the reduced "throw" (i.e., angular range of motion of the controller) of drive-by-wire human-machine interface (HMI) devices such as yokes and joysticks, as compared with the conventional steering wheel. In particular, because of its essential role in defining the behavior of the steering system, the characteristics of the shaping function and how it affects driving performance will be our focus. We first present a summary of the basic issues associated with steer-by-wire vehicles that use nonstandard control devices, followed by a brief discussion of the variety of approaches to solving these issues by means of variable gear ratio steering systems.

3. Drive by Wire and Control

Future military vehicles will be drive-by-wire (DBW) vehicles, which means that mechanical elements of the control system are replaced by operator-controlled input devices coupled with remote actuators via a central electronic control system (Mammar, Sainte-Marie, & Glaser, 2001; Yih & Gerdes, 2005). A DBW vehicle can be composed of several "*x*-by-wire" subsystems. Examples include steer by wire, brake by wire, and throttle by wire, each referring, of course, to the individual vehicle control subsystems for which direct mechanical linkages (such as the hydraulic brake line) have been replaced by electrical signals between the input device (e.g., brake pedal) and the actuators of the system (e.g., calipers). In this report, we are specifically interested in steer-by-wire subsystems, an example of which is shown in figure 2b. While the issues we address have analogues in other *x*-by-wire system components, we will not directly address their influence on driver performance.

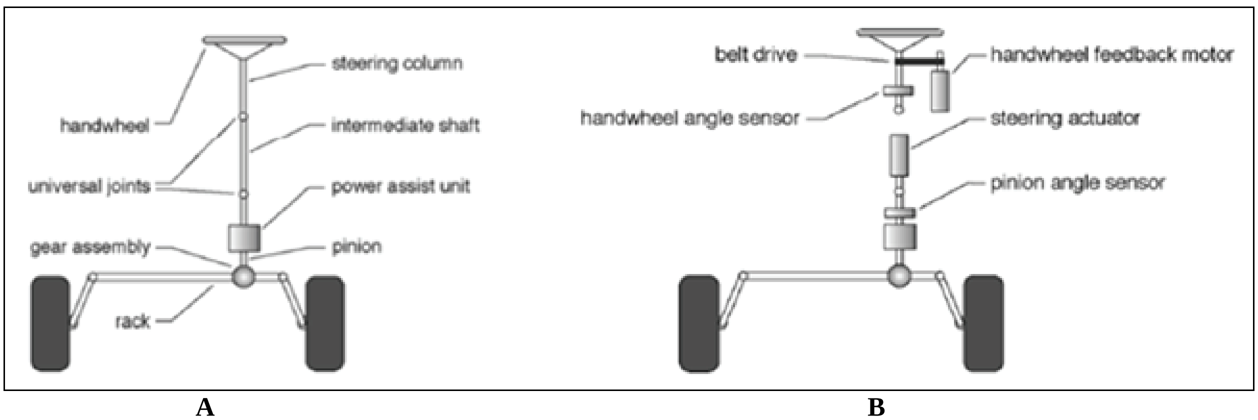

Figure 2. A comparative example of the difference between conventional (A) and by-wire (B) steering systems. (Images are adapted from Yih and Gerdes, 2005, p. 966, figures 1 and 2.)

Because the actuators in *x*-by-wire systems are controlled by electrical signals from a computer rather than a direct mechanical link to the HMI, input from the driver can be supplemented with or modified by intelligent automation. A good example of such automation in civilian vehicles is adaptive cruise control (ACC). An ACC system is used in a manner similar to standard cruise control except that after the driver sets the desired speed, an adaptive controller regulates spatial separation from other vehicles on the road as well as attempts to maintain the speed indicated by the driver (c.f. Kelber et al., 2004; Rajamani & Zhu, 2002). The commercial automotive industry views by-wire and associated technologies such as ACC as advantageous because they enable new design options in terms of packaging vehicle components, integration of intelligent performance- and safety-enhancing control features, and reduction in noise. In the case of by-wire steering, ACC can mean increased safety for the driver because there is no steering column that could invade the vehicle cabin during a front-end collision (Chiappero & Back, 2002; Fowler, 2003).

The successful implementation of intelligent driving systems such as ACC facilitates our discussion of military applications by highlighting useful alternatives to traditional control. Of particular interest are intelligent systems that allow user specification of vehicle motion without explicit need for direct and/or continuous input. Intelligent vehicle systems provide designers the opportunity to develop and integrate a range of controllers that ultimately may increase overall system performance and may reduce the workload associated with mobility-control tasks (Kelber et al., 2004; Stanton & Marsden, 1997). At the same time, such advances in vehicle technology and non-traditional controls place a greater emphasis on the importance of careful interface design and implementation and how these advances influence human driving performance (Walker, Stanton, & Young, 2006).

Clearly, the integration of by-wire technology and associated non-standard control devices such as joysticks into vehicle control systems has significant potential to improve driving performance and vehicle safety during mobile operations while decreasing vehicle space claims and operator training time (Andonian et al., 2003). Successful implementation of by-wire and other related technologies, such as vehicle safety features (e.g., antilock brakes, dynamic stability control) and electric power steering (EPS), into current automotive industry production lines supports the position that intelligent systems can be extrapolated into capabilities such as active steering, which may augment the driver's input to improve stability and maneuverability. Such systems have demonstrated advantages in civilian driving during tasks including lane maintenance (Rossetter, Switkes, & Gerdes, 2004) and path selection (Shoemaker, Bornstein, Myers, & Brendle, 1999) and are ultimately thought to offer improvements in performance (Ackermann & Bunte, 1997; Kasselmann & Keranen, 1969; Yih & Gerdes, 2005).

4. The Human Operator

Despite dramatic improvements in intelligent, adaptive technologies for vehicle control systems, the time when the role of the human changes from operator to passenger remains in the distant future. The essential role of the human within the control loop has long been recognized as the best possible solution to the difficulties associated with developing systems that are robust enough to account for the myriad of contingencies presented by an open, dynamic task environment (Parasuraman, Sheridan, & Wickens, 2000; Parikh, Grassi, Kumar, & Okamoto, 2007; Sellner et al., 2006; Sheridan, 1992). Accordingly, research and development efforts continue to incorporate the human as an integral element in the operation of the physical driving system. That is to say, although issues of vehicle autonomy are an important consideration within future military vehicle programs, we do not explicitly focus on autonomous vehicles within this current discussion of steer-by-wire systems. Instead, throughout our discussion, we focus on the *interaction between*

the human operator and the by-wire steering system as the primary locus of potential control difficulties.

Control theory-based models, which formalize the description of information flow from input to output, are frequently used to guide the design and analysis of complex physical systems. Likewise, in modern research, control theory models are employed with increasing frequency to facilitate a mechanistic understanding of input-output relations in human performance, both independent of (Todorov & Jordan, 2002) and during interactions with physical systems (Huang, Smakman, & Guldner, 2004; Sövényi & Gillespie, 2007). There is a broad literature available about human performance from the perspective of engineering and control theory (c.f. Jagacinski & Flach, 2002; Wickens & Hollands, 2000). Within this literature, it is clear that humans are understood to be particularly adept at tasks requiring certain types of control, such as the flexible decision making and adaptive reasoning required in unexpected situations. However, at the same time, humans have degraded or limited performance in tasks requiring other forms of control such as those that require rapid actions and decisions in the presence of lagged feedback regarding system response to control input (c.f. Sheridan, 1993).

Wickens and Hollands (2000) suggested that human performance is specifically limited by its fundamental information-handling capabilities such as processing time, information transmission, prediction and anticipation, perception of higher derivatives (e.g., velocity, acceleration), and processing resources. In general, as the amount and complexity of information that the human is required to process increase, performance tends to decrease. For example, it is well known that the rate of information transmission, as reflected in the time required to perceive and react to a given stimulus (i.e., reaction time), is slowed by a number of factors, including increased age of the performer, number of response choices, degraded detectability of the stimulus, incompatibility between the stimulus and the response and number of actions that must be planned and performed following the stimulus cue (Schmidt & Lee, 1999).

Increased semi-autonomous operations will be enabled by *x*-by-wire implementations, accompanied by enhanced functionality for the operator through the Soldier-machine interface (SMI). This is very likely to place a high demand on the human operator's limited information processing resources (McDowell et al., 2007, 2008; McGovern, 1987). As a direct consequence of the reduced crew size and increased in-vehicle technology, the operator will be required to attend to a greater number of tasks simultaneously. Examples of such overlapping tasks include maintenance of a supervisory level of control over vehicle mobility requiring frequent monitoring and periodic assumption of control over the vehicle while concurrently scanning the local area for potential enemy activity and attending to vehicle status variables such as engine temperature and fuel level (McGovern, 1987). Accordingly, the impact of enhanced vehicle technology on aspects of human performance that are potentially compromised by increased workload and attentional demands must remain a high-priority consideration for system designers in optimizing system performance and safety.

A variety of arguments has been forwarded in specific reference to human factors considerations for by-wire vehicle design (Stanton & Marsden, 1997; Stanton & Young, 1998; Walker et al., 2006). For example, Stanton and Marsden (1997) evaluated three generalized human-centered justifications for incorporating automation in ground vehicles; these included potential improvements in driver well-being through reduced stress, frustration and workload, removal of human error from the control loop, thus reducing likelihood of accidents, and increased commercial and consumer options positively affecting sales in the automotive market. Of course, concern was also raised that automation could introduce negative performance outcomes unless well conceived and applied. For example, Stanton and Marsden considered possible "error-inducing equipment design" as sufficiently important to merit inclusion among the four main possible sources of problems in future by-wire systems. The other three major sources of problems included (a) shortfalls in the expected benefits of implemented systems; (b) changes in operator expectations and level of vigilance based on reliability of the automated system (problems were cited for unreliable as well as "overly reliable" cases); and (c) a loss of operator skill and responsiveness to training as a by-product of diminished perceived relevance of the skill set for the operation of automated systems. The human factors issues associated with the shaping function that specifies the relationship between HMI commands and vehicle heading, touch on a number of these potential sources of problems. In addition to the obvious association with "error-inducing equipment design," it is possible that a poorly selected shaping function could have negative consequences for operator perception of vehicle reliability as well as simply having shortfalls in expectations based on the intent of the design.

5. Improved Vehicle Control With the Use of a Steering Shaping Function

For the purposes of our research, we define a shaping function as a mathematical description of the scaling between the input and output of a given system, that is, how the input is "shaped" into output. This is similar to the concept of a transfer function, except that the transformation is not explicitly occurring in the frequency domain. For steer-by-wire systems, the shaping function maps the angular displacements of the HMI control input device (joystick, yoke, or steering wheel) to the system response in terms of the vehicle steering angle. The examination of shaping functions is important for several reasons. First, the use of HMI devices with limited "throw," or total angular range of displacement, will pose challenges to the operator. A specific consequence of limited throw is the magnification that the operator will perceive relative to his or her expectations, based on experience with standard vehicles with steering wheels. In other words, because of the smaller permissible angular range of alternate HMI, there will be a lower input position-to-wheel-angle ratio (also known as the steering ratio), and therefore, smaller hand/arm motions will produce larger vehicle responses. A second issue involves the need for differential steering sensitivity across various driving tasks. Consider, for example, the large angular range of steering motion required for parallel parking as compared with the relatively small motions needed for lane

maintenance while one is driving on a highway (Huang et al., 2004; Olson & Thompson, 1970). Now envision the variety of steering tasks that may be encountered on the battlefield or during off-road missions in military vehicles. Such task factors are further compounded by the third issue: vehicle speed. In particular, as the vehicle moves faster, the magnitude of lateral accelerations during steering increases, elevating the risk of oversteering, inducing excessive roll or loss of control leading to collision, spinout or rollover (Ackermann & Bunte, 1997; Sakai, Yoneda, & Shimizu, 2004). An advantage to the electronic control used in steer by wire is that the steering ratio does not have to be fixed, but rather, it can be modulated adaptively across platforms, tasks, and speeds to help account for these performance and safety issues (Andonian et al., 2003).

The primary approach to overcoming the problems mentioned has been to implement variable gear ratio (VGR) steering systems. The gear ratio in a steering system provides a description of how much angular displacement of the steering wheel is required to produce a particular angular displacement of the vehicle heading via turning of the wheels. For instance, if one complete revolution (360 degrees) of the steering wheel results in the wheels of the vehicle turning 20 degrees, then the steering ratio is 360/20, or 18:1. A higher ratio means that one has to give greater input (thus expending more energy) to get the wheels to turn a given distance.

There have been, of course, different mechanisms for implementing VGR systems. We categorize the VGR systems as speed variable [sVGR]), which scale the ratio as a function of vehicle speed, or angle variable (nVGR), which scale as a function of HMI input angle. VGR steering systems have been proposed and studied since the 1960s (Huang et al., 2004; Olson & Thompson, 1970; Wohl, 1961). Typically, modern VGR systems are of the sVGR type that work by using an active steering system (such as electronic power steering [EPS]) to minimize the ratio at low vehicle speeds, reducing the amount of steering wheel motion required to make large maneuvers, and then increasing this ratio progressively as vehicle speed increases, thus minimizing the influence of minor hand motions that the operator may make while driving at higher speeds. Such systems have already been introduced in the commercial automobile market and are currently considered a selling point for higher end vehicles and thus, are the types of systems that have received the most attention.

An alternative to speed variable systems is available in the form of the nVGR implementation. With an nVGR system, the steering ratio scales as a function of the operator input rather than the vehicle motion. Specifically, the response of the wheels to a given angular displacement of the HMI will vary, depending on the current angular position of the interface. For example, in a 16-8:1 nVGR system actuated by a yoke, a 2-degree input issued from the central position of the yoke would result in a 16-degree steering angle, but that same input issued when the yoke is near one of its extreme angular positions would result in a 32-degree steering angle. For conventional vehicles that have a steering column, such as those using a rack-and-pinion mechanism, one can achieve nVGR by simply changing the spacing between the gear teeth as the angular distance from the central position increases. For by-wire systems, the same results can be obtained in a more flexible manner through the use of an appropriately defined shaping function that specifies

the scaling relationship between the HMI and wheel angle across the range of possible steering inputs.

The use of a shaping function can eliminate the need for or facilitate the function of an on-line, dynamic control system that monitors vehicle motion and changes the steering ratio from one speed condition to another. That is, if one considers that high-speed driving is most commonly associated with a very small range of steering input and lower speed maneuvering (such as parking) uses much more of the dynamic range of the steering wheel, then a nonlinear shaping function that applies a high ratio for small steering input and a lower, more direct ratio for large input will effectively match the steering ratio to vehicle speed by virtue of the task that the driver is performing. At the same time, one can envision dynamic selection of shaping functions that are optimized for particular vehicle operation scenarios in order to smoothly change steering characteristics in an on-line fashion when a different vehicle response is required.

A current approach for by-wire military vehicles employs a nonlinear shaping function to map steering input to wheel angle. The nonlinearity in the current shaping function is attributable to a dead spot (an area of no system response) around the zero point (null position) of the HMI, combined with active regions to either side of the inactive dead spot where output increases linearly as a function of steering angle. The prominence of the dead spot is important because of continuous, subtle input from the operator around the central position, which must be minimized in order for the steering output to stabilize (Jagacinski & Flach, 2003). This is particularly true for velocity or higher derivative-based motion control systems because small fluctuations, such as noise, tend to be significantly magnified with each higher derivative used in the control loop. To facilitate stabilization of wheel angle, we have made the dead spot more prominent by defining a broader angular region around the null position throughout which there will be zero input to the steering system; this null region is known as the dead band. The boundaries of the dead band are defined by a “psychophysical edge” where the driver can “feel” (perceive) a change between the inactive and active regions. In essence, this dead band acts as a low-pass filter so that the effects of small amplitude, high frequency steering input around zero are removed while large amplitude, low frequency steering input are allowed to influence the system’s behavior. An important justification for inclusion of this dead band is illustrated by the phenomenon of “biodynamic feedthrough” in which vibrations of the vehicle are transmitted to the HMI through the operator in a purely mechanical manner (Sirouspour & Salcudean, 2003; Sövényi & Gillespie, 2007). Obviously, it is not desirable for jostling of the vehicle to affect steering input from the driver, particularly in critical situations such as evasive maneuvering where speeds are higher and vehicle motion is more vigorous.

Regardless of how the system is implemented, it appears as if VGR steering has the potential to be a performance- and safety-enhancing control option (Huang et al., 2004; Kelber et al., 2004; Limpibunterng & Fujioka, 2004; Sakai et al., 2004; Yih & Gerdes, 2005). Although its application in conventional vehicles has yet to become standard, how to make decisions regarding the particulars of the VGR implementation remains an important engineering challenge for steer-by-

wire systems. That is, by virtue of the way in which by-wire systems function through the intermediary of a computerized control system, designers must confront the question of how best to transform control input from the HMI to the steering actuators (Andonian et al., 2003; Östlund & Peters, 1999; Peters & Östlund, 2005). Fundamental to answering this question are the human factors issues raised by nonlinearities implemented in vehicle control through the steering shaping function. In other words, it is essential to understand the effects of different parameters of VGR steering on human performance during military vehicle driving.

6. Shaping Functions, Variable Steering Ratios, and Driver Performance

When one is considering performance difficulties in HMI, the interface should be one of the primary system elements assessed as a potential source of error. The functional capacity of the driver-vehicle system will be defined in large part by the interaction between the capabilities of the operator and the operational characteristics of the HMI. By-wire systems provide a myriad of possibilities in terms of the HMI devices that can be used for vehicle control. This flexibility, combined with a general lack of complete understanding of human factors issues associated with these interfaces, creates a level of ambiguity with respect to the establishment of design standards regarding ideal operational characteristics for steer-by-wire vehicles. Moreover, the potential that any number of interface-driver combinations may be used with a given by-wire vehicle demands that software is adequately programmed to map (a) driver preferences, (b) the dynamic angular range of the HMI, and (c) that of the vehicle to one another in order to provide intuitive control while optimizing steering input for the physical dynamics of the controlled vehicle.

In what follows, the effects of VGR systems on human driving performance are assessed in order to generate conclusions regarding the structure that the shaping function of the HMI implemented in some by-wire vehicles. Although the effects of using VGR systems on driving performance constitute an important area of research within the commercial automotive industry, few results have been made available through the peer-reviewed literature (presumably owing to proprietary issues). This is particularly true in terms of assessing how these results translate to military platforms. As such, the available information is reviewed and assessed as a general guide for interpretation of expected effects of the shaping function on Soldier performance in military situations. Our discussion takes as a starting point that there are three main issues to consider: (a) the limited angular range of motion ("throw") of the HMI, (b) the interaction between throw and vehicle speed, and (c) individual differences among and within human operators in terms of driving style and task effects.

6.1 Angular Range of Motion ("Throw") of the HMI

Critical to the current review is the fundamental issue that different HMI devices are built with different amounts of throw. Consider, for example, that many conventional steering wheels can

be turned ~3 to 3.75 revolutions within the physical limits of the system, yielding approximately ±540 to ~675 degrees of allowable motion. On the other hand, joysticks, which are the preferred HMI for use in the CAT (primarily because of physical space constraints within the vehicle), are typically limited to a ±20- to ~40-degree dynamic range (Andonian et al., 2003; Östlund & Peters, 1999; Peters & Östlund, 2005). To translate these angular motions to a more intuitive metric, Östlund and Peters provided an example of how a driving movement requiring a 20-degree displacement of a conventional steering wheel could be accomplished with a 0.6-degree displacement of a joystick, which would mean that the operator would only need to move his or her hand 1 mm to induce a significant change in vehicle heading. As applied to military platforms, such as a 20-ton, 8-wheeled light armored vehicle (LAV), a ±60-degree yoke would result in a linear steering ratio of approximately 1.6:1. This contrasts with steering ratios used in conventional automobiles that are nearly an order of magnitude higher, typically around 14:1 (Olson & Thompson, 1970; Sakai et al., 2004; Schulze, 1981; Tongue, 2005).

The practical significance of reduced throw in most by-wire HMI devices as compared with a standard steering wheel is that it simultaneously allows subtle hand movements to provide fine-grained control over vehicle motion, which may be a benefit, but it also considerably increases the potential for control degradation because of inadvertent input resulting from biodynamic feedthrough (Sirouspour & Salcudean, 2003; Sövényi & Gillespie, 2007), limb positioning errors (Allen & Proske, 2006), or small, unintentional postural adjustments of the operator (Treffner, Barrett, & Petersen, 2002). That is, with the magnification of the relationship between hand movement and vehicle response, it is likely that *all* accelerations, whether they are of the vehicle or the operator, will be physically transmitted to the HMI and will thus serve as unintended control input. For instance, centrifugal acceleration during a sharp turn could cause a driver's body to be thrown outward (i.e., away from the turn), and this could result in a counter-steering motion translated to the HMI that would disrupt the execution of a smooth and controlled turn of the vehicle. This issue is particularly salient for tasks that tend to occur at higher speeds, such as lane keeping, where movements of a steering wheel in a conventional vehicle are on the order of 5 to 10 degrees (Andonian et al., 2003) but would be on the order of 0.5 to 1 degree in the alternate HMI by-wire vehicle. As the allowable range of motion in the HMI is reduced, it is very likely that the amount of steering errors may be increased by virtue of limits on the resolution of the human capability to sense and precisely control limb position. For example, recent evidence suggests that perception of arm positioning in a typical human adult may only be accurate to within 1 to 2 degrees and during fatiguing circumstances, the errors in positional sensation/perception can increase nearly five fold (Allen & Proske, 2006; Walsh, Hesse, Morgan, & Proske, 2004). Taking such basic functional aspects of human physiology into account should therefore constrain engineering decisions regarding the lower limits of the functional range of a steer-by-wire HMI device.

6.2 The Interaction of Speed and Throw

The issue of reduced throw in by-wire interfaces for driving is complicated by considerations of the speed at which the vehicle is to be controlled. Common wisdom, as well as considerable research, suggests that even without the issue of limited throw, task speed is a major factor affecting human performance (Plamondon & Alimi, 1997; Schmidt & Lee, 1999), and this relationship between task speed and performance has had considerable influence over developments within the domain of human-computer/human-machine interaction (Seow, 2005). Even from a purely physical standpoint on the task of driving, as a vehicle moves at increased speeds, the effects of heading variations in terms of lateral accelerations and likelihood of losing vehicle control (oversteering, spinout) are significantly increased (Ackermann, 1998; Ackermann & Bunte, 1997; Limpibunterng & Fujioka, 2004; Sakai et al., 2004). This physical reality becomes a critical variable when we examine the relationship between driver input and vehicle output as well, and this rationale served as the basis of one of the earliest investigations of VGR systems: "… [in order] to provide precise control at high speeds and maximum insulation from road shock, the ratio should be high. On the other hand, to minimize steering-wheel turning and provide easier low-speed maneuvering, the ratio should be low. An obvious solution is a variable-ratio steering gear" (Olson & Thompson, 1970, p. 553).

The work of Olson and Thompson (1970) was among the first peer-reviewed publications that indicated an impact of the steering ratio on both actual and (self-) perceived operator performance during driving. While not an explicit study of sVGR systems, Olson and Thompson used nVGR systems to examine driver performance and perception across a number of tasks requiring different speed-lateral acceleration combinations (i.e., variable ratio gears included 16-12.2:1 and 16-8:1; fixed ratios included 11:1, 13.5:1, and 16:1). Summarily, it was observed that drivers generally gave vehicles with VGR systems higher subjective ratings regarding perceived controllability as compared with fixed ratio vehicles, and these subjective ratings were supported with statistically verified performance improvements during low-speed parallel parking (e.g., reduced parking time). Performance enhancements, however, were not statistically supported for a continuous motion, higher speed lane-keeping task along a curvilinear path. Additionally, for all conditions, drivers indicated nearly ubiquitous dislike of the more "extreme" of the VGR systems used (16-8:1), specifically citing increased perception of vehicle roll during sharp cornering as problematic and suggesting that the steering may have been too sensitive in that system. The important message to be taken from these qualitative reports, together with the variations in patterns of statistical significance (or lack thereof) across conditions, is the notion that task factors involving speed and lateral acceleration are important considerations for VGR system design in terms of vehicle performance and operator perceptions affecting trust in the vehicle. Although Olson and Thompson cautioned against drawing broad conclusions from their initial assessment of VGR systems, it is reasonable to conclude that VGR steering did not degrade performance, and further, some evidence was found that a VGR system, appropriately calibrated to speed, could facilitate improved vehicle control and operator perceptions.

Unlike the nVGR systems assessed by Olson and Thompson (1970), modern VGR systems are often of the speed-variable variety. The rising popularity of sVGR can be logically attributed, at least in part, to its ability to be actuated by the already established electronic or electro-hydraulic power steering systems and, of course, further encouraged by the expectation of eventual transition to complete electronic vehicle control as will be the case in future steer-by-wire systems. BMW (Bayerische Motoren Werke), for instance, is among several producers of high-end vehicles that have integrated sVGR into their commercial offerings; others include Lexus, Toyota, Audi, and Honda. Such systems are generally known on the commercial market as "active steering" (AS) or "active control steering" (ACS) systems. Active steering systems electronically vary the steering gain (i.e., ratio) as a function of the steering wheel angle and the current movement state (speed, lateral/yaw acceleration) of the vehicle. In such systems, during normal, low- and medium-speed driving conditions, the steering ratio is designed to be approximately direct. This means that the gear ratio is low and the wheels respond with a greater angular displacement for a given amount of steering input from the driver. As a result, the amount of work that the driver must do to accomplish typical low-speed maneuvers, such as navigation around a tight corner in a cramped space, is reduced as compared with a vehicle using a fixed steering ratio. As the vehicle control system detects increasing speed, it then adjusts the steering ratio to decrease sensitivity, thus reducing the magnitude of steering response to driver input and therefore, the likelihood of maladaptive responses such as oversteering. In more extreme circumstances, such as when driver input is inappropriate and would lead to vehicle destabilization, a sophisticated controller algorithm could literally take control from the driver and minimize or even cancel the influence of his or her steering input (Tongue, 2005).

As one of the first widely available sVGR systems, the BMW's 5-series hybrid active steer system is useful as a detailed example (DeMeis, 2003; Sawyer, 2003; Tongue, 2005). Consistent with the speed-variable control principles already discussed, fewer than two full turns of the steering wheel in a 5-series BMW are needed to achieve maximal change in steering angle ("lock to lock"), and thus, the low-speed steering ratio is more direct (on the order of 10:1) whereas at higher speeds, the ratio can reach a maximum of 20:1. Moreover, redundancy is built into the system so that if the active steering fails, there is a mechanical "backup" that reduces steering to the baseline function of a standard, fixed ratio (14.1:1) system. Figure 3 shows the variable steering ratio as implemented in BMW's active steering system; note the nearly 50% reduction in driver effort during normal driving at 50 kph (~31 mph) for the actively variable (blue line) as opposed to a constant ratio system (red line). In more extreme circumstances, by contributing as much as 2.5 degrees of front wheel countersteering, this active steering system can facilitate recovery from potentially hazardous incidents by avoiding activation of the oft-disconcerting dynamic stability control (braking) system of the vehicle (DeMeis, 2003).

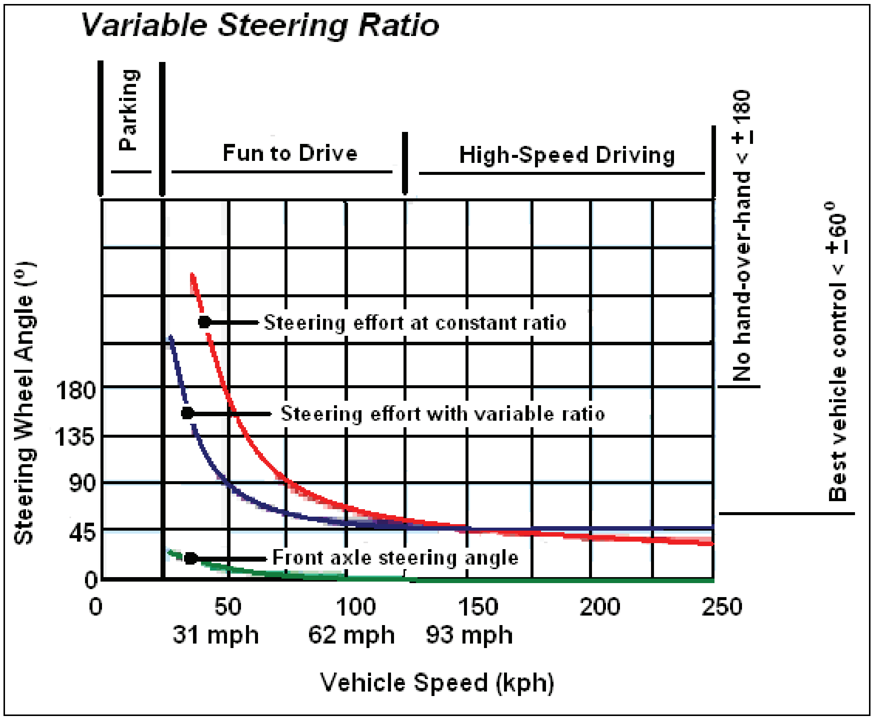

Figure 3. BMW's active steering system is based on varying the steering ratio, depending on vehicle speed. (Image adapted from DeMeis, 2003.)

Although the BMW active steering system has received a bit of attention in the published media, no direct information regarding how this system affects human performance has been evidenced through peer-reviewed data reports. At the same time, a variety of model-based assessments has been used to mathematically infer how sVGR systems analogous to active steer have potential to attenuate the influence of maladaptive driver input during critical situations (Azzalini, Gissinger, Boussouar, & Coutant, 2002; Huang et al., 2004; Limpibunterng & Fujioka, 2004; Sakai et al., 2004). For example, Sakai and colleagues developed a cable-type VGR steering system for Honda and, through a combination of model-based quantitative and qualitative analyses, were able to show enhanced performance in avoidance of a spinout (Sakai et al, 2004). In essence, Sakai and colleagues were able to achieve VGR steering characteristics by using the physical properties of a flexible cable that has lowered torsional rigidity (reduced stiffness) in place of a standard steering column. Because of its physical load-deformation properties, the cable-type EPS system had a steering response that was proportional to the magnitude of self-aligning torque experienced by the wheels of the vehicle; the torque itself was a function of steering angle and vehicle speed. Active torque control components of the system were used to compensate for phase lags, that is, delays in the timing of the steering response induced by the physical mechanics of the cable. Computational simulations demonstrated how this type of sVGR system could facilitate the avoidance of and recovery from spinout attributable to oversteering *across a range of driver capabilities*. That is, not only was this system superior to fixed gear ratio systems for enabling safe maneuvering in the extreme situations, but it was also shown as able to tolerate a larger range of lags in the time it

took for the human driver to initiate corrective steering action (e.g., slowed reaction times) as compared with more rigidly actuated systems, such as those using a standard steering column.

Using a similar analytic method but guided by some earlier empirical data regarding human performance in VGR systems (specifically, data from Schulze, 1981), Huang et al. (2004) mathematically verified that improvements could be made with VGR systems but added that the variation in the gear ratio should be based on different information within different speed ranges. Specifically, through closed loop analyses, it was shown that at speeds below ~25 km/h (~15 mph), the driver prefers a fixed steering ratio, and thus, position-based feedback control is optimal. In such a zeroth order system, the angle specified by the HMI should thus be proportional to the curvature of the vehicle path. In other words, the operator should control the vehicle at low speeds through a shaping function based on the steering wheel angle alone. Huang et al. further observed that at intermediate to higher speeds (~25 to ~45 km/h and above), drivers appeared to prefer steering systems that maintain constant yaw gain, that is, a constant rate of change in vehicle yaw (vehicle heading angle with respect to a directly forward path) as a function of HMI angle (figure 4). Therefore, it was concluded that in intermediate to high speed ranges, the driver primarily uses rate information (i.e., first order control) to select the appropriate HMI angle. This theoretical analysis gains a modicum of support from the earlier data of Olson and Thompson (1970) that revealed lack of performance enhancements for drivers using nVGR systems in lane keeping as compared with parallel parking. Perhaps if Olson and Thompson had been able to implement a rate-based VGR system for their higher speed tasks (recall, nVGR is based only on steering wheel angle), they would have seen benefits throughout their experimental conditions rather than only in parallel parking.

Although data regarding human performance with specific, commercially available sVGR systems such as BMW's active steer tend to be sparse, a number of research groups have assessed performance effects of the types of advanced systems that form the basis of those implemented in commercial models. In the studies where sVGR components were included, data have been presented which support the idea that driver performance in by-wire systems can be equivalent to performance of a standard steering system (Yih & Gerdes, 2005) and in certain cases, performance can be enhanced (Kelber et al., 2004). Unfortunately, there are two main problems precluding heavy reliance on data from most of the available studies. First, while experimental design was usually reasonable in terms of inclusion of appropriate control conditions, the data sampling, selection of measures, and subsequent analyses were not generally conducted in a manner that allowed verification of qualitatively observed differences through proper use of inferential statistics. Second and more problematic for the interpretation of the unique influence of sVGR on driver performance is that most studies that have identified performance equivalence or enhancements have included sVGR as part of larger active steering systems and thus, did not assess its independent contribution to driver performance. Accordingly, although it can be inferred that sVGR is an important component of an overall performance-enhancing system, few conclusions can be drawn regarding the specific implementation details that optimize vehicle

safety and driver performance. To speak about this last point, a small amount of information was found in an early simulator study of sVGR as compared with a number of fixed ratio systems (Schulze, 1981). As with other studies in this domain, inferential statistics were not provided to verify that qualitative patterns of difference were real (beyond differences attributable to measurement error); however, this study presented evidence that indicated sVGR in the range of 20-6:1 leads to driver-perceived performance enhancements when civilian vehicles are being operated. Specifically, based on simulated driving with a variety of gear ratios, data (shown in figure 5) revealed that drivers preferred the two sVGR systems over fixed ratio systems. Similar to work from a decade earlier (Olson & Thompson, 1970), differences were seen in terms of driver-perceived ease of use, vehicle responsiveness, and magnitude of steering movements required to induce a change in heading direction.

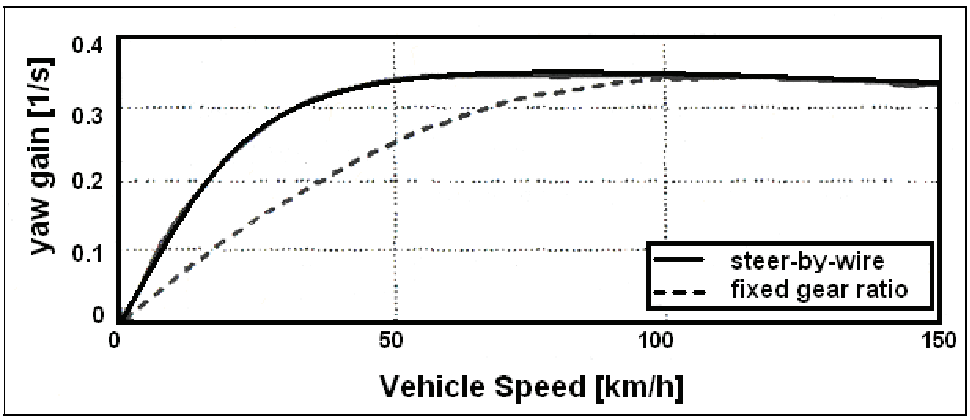

Figure 4. Experimentally observed yaw gain as a function of vehicle speed, for both variable steering ratio (steer-by-wire) and fixed ratio (conventional vehicle). (Image adapted from Huang et al., 2004.)

Overall, it appears that the appropriate selection of a shaping function requires consideration of two primary factors, including the operational range (throw) allowed by the HMI as well as the vehicle speed and lateral acceleration. Although each type of VGR system (sVGR, nVGR) has been predicted and/or shown to be associated with limited improvements, it seems that the evidence suggests their combination may lead to even greater benefits. Yet, the discussion to this point leads to another, more complex issue that must also factor into engineering decisions regarding the selection and specification of the shaping function. That is, it appears as if all the previous work has had to contend with and has been limited by inter-individual variability in terms of the driving style, expectations, and perceptions of human operators. That is, in addition to varying by speed and range of steering input, it is likely that the optimal shaping function will need to vary according to the driver and/or the vehicle response desired for execution of a particular maneuver or task.

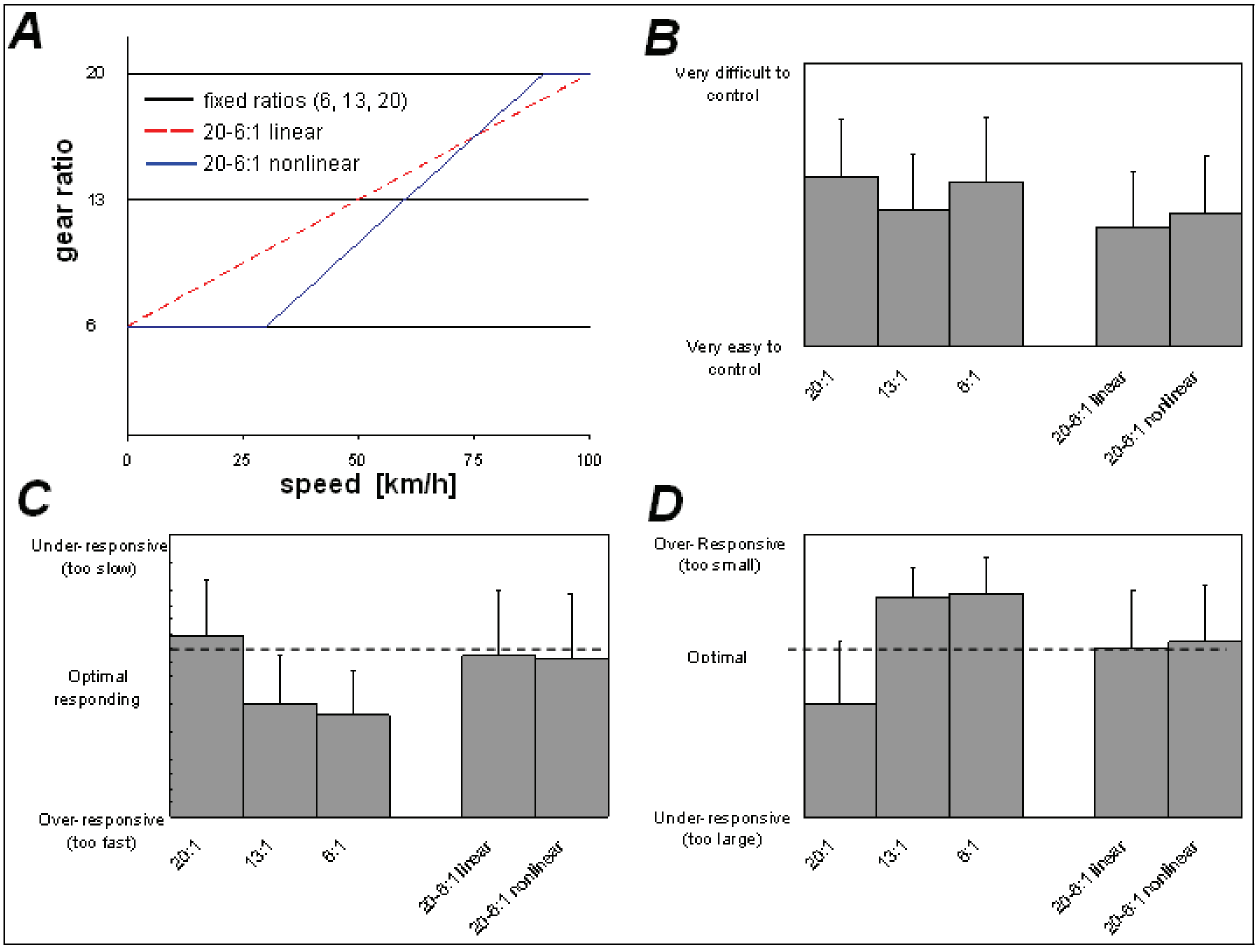

Figure 5. Results from simulated driving with a variety of gear ratios: (A) depicts the "shaping functions" for the five different gear ratios tested (three fixed: 6, 13, 20 and two variable: linear and nonlinear 20-6:1). The remaining graphs represent driver ratings of each gear ratio based on perceived ease of control (B), vehicle response on fast movements (C), and required steering angle (D). (Images are adapted from Schulze, 1981, p. 339, figure 1.)

6.3 Considerations of Variability Attributable to Task and Individual Operator Differences

Clearly, as the preceding discussion has emphasized, the types of maneuvers to be performed impact the desired response characteristics of the vehicle and thus weigh heavily as considerations for the development of an appropriate shaping function. As has been emphasized throughout this discussion, the relative success of a given driving maneuver will be determined by both the execution speed and HMI input. For example, parallel parking is a low-speed, large motion maneuver in which the steering wheel is often turned more than 180 degrees. Lane keeping, on the other hand, can be high speed and only requires small movements of a steering wheel that are on the order of 5 to 10 degrees. Yet, vehicles are not always handled in these "typical" manners. High-speed maneuvers can require sudden onset, large steering input that would benefit from a more direct gear ratio. Examples of high-speed maneuvers include avoiding obstacles, responding to unexpected environmental disturbances (e.g., lateral wind gusts), or executing intentional extreme

motions (e.g., evasive cornering). The real possibility of needing the capacity to perform such infrequent (and often risky) maneuvers provides an interesting instance in which active control systems with "intelligent" specification of the shaping function might actually cause control difficulties.

Because the emphasis of most development efforts in the domain of intelligent control systems is to maintain performance within a large margin of vehicle safety limits, accounting for extreme maneuvering capabilities tends to be of lower priority. As a result, it is possible that situations may arise when an otherwise skilled driver attempts to provide input that conflicts with the intelligent control system in a catastrophic manner. Tongue (2005) described this potential problem through the example of professional race drivers who are required to push their vehicles to physical limits while executing frequent and rapid transitions between high- and low-speed states. Consider, for example, how racers have to navigate turns; usually, the approach occurs at the high speed used through the straightway, followed by a purposeful, discrete, and sudden application of the brakes to manage the turn and then a quick acceleration as the turn is completed to resume the race. The problem exists in that the speed at which this task unfolds is high, and thus the duration over which the rapid cycling between low and high speeds is rather short. Therefore, if standard sVGR principles were implemented, the driver would be challenged to pilot the vehicle through the turn, based on a steering ratio that was suddenly much more direct than that which s/he was acclimated to just milliseconds before, amplifying the vehicle response to steering input and quite possibly causing the driver to enter a dangerous (and potentially fatal) oversteering situation. The converse could also be true for a rapid low to high speed transition. This example illustrates just one of many potential situations in which skilled driving actions will conflict with most of the steady state assumptions on which intelligent steering systems are built. Although it is not assumed that military drivers would be intentionally racing their vehicles, an appropriate solution for relating driver input to vehicle output will need to consider the various types of atypical and risky driving maneuvers that could be encountered. Perhaps a potential solution would involve the implementation of a mode toggle that allows the driver to switch between shaping functions that are tailor-made for various possible control scenarios and tasks, such as evasive maneuvering versus lower speed off-road reconnaissance driving.

Aside from control variations attributable to task factors are variations brought about by the intrinsic variability between and within human operators. It is quite possible that the particular driving style adopted by one operator could vary according to (a) the information used as feedback for steering decisions (Huang et al., 2004); (b) the aspect of vehicle behavior that the driver prioritizes for optimization/minimization during movement (Limpibunterng & Fujioka, 2004); (c) the level of experience with the vehicle, HMI or driving in general (Andonian et al., 2003); or (d) simply the intrinsic neuromotor dynamics of the person (Riley & Turvey, 2002). In a human factors study of simulated driving via a joystick, for instance, Andonian and colleagues observed that their pattern of results varied considerably with the level of driving experience of each of their participants; those who were least experienced tended to show greater performance differences

between a standard steering wheel and a joystick, whereas those with the greatest amount of experience tended to perform well regardless of the specific HMI they used. Modeling efforts such as those of Limpibunterng and Fujikoa have demonstrated that with sufficient study and human-vehicle system identification efforts, it is feasible to develop implementations that account for such individual differences with configurable control system parameters. Other approaches, such as the active, cable-type EPS system discussed earlier (Sakai et al., 2004), have shown that it is also possible to design systems that are relatively robust to individual differences in certain human response variables, such as the operator reaction time.

Perhaps the most critical step toward improving control in VGR systems will likely come as systems researchers and designers gain an increasingly comprehensive understanding of the intricate *relationships between the sources of variability*. That is, it is very likely that constructs such as "driving style" are not best conceived as static personality characteristics of an individual driver but can vary according to other characteristics of that driver, such as level of experience with a given platform, basic neuromotor control capabilities, level of fatigue, and other factors. In addition, environmental variables can and do interact with vehicle performance in terms of sensor performance, surface traversibility, presence of potentially crippling hazards, and so on. Finally, the vehicle's dynamics are changed as a result of how the driver drives the vehicle. Better understanding of these types of interactions between driver environment and vehicle will continue to push the refinement of control systems to greater levels of sophistication.

7. Summary

Modern vetronics technology is at the forefront of U.S. Army efforts to establish an unparalleled future force that increases effectiveness while reducing the costs of military engagement. As such, the need for solutions to the technologic challenges that are slowing the advancement of intelligent systems has become critical. This review was intended to examine performance issues associated with the shaping function that defines the vehicle response to steering input. The overall purpose of our efforts is to support the identification of design parameters critical to improving the implementation of by-wire systems within military tactical vehicles and ultimately, to optimize system performance for execution of secure mobile operations.

Among the issues associated with the selection of an HMI appropriate to control specialized military vehicles is the *relationship between* vehicle motion and the operator's ability to control that motion. Main factors affecting the ability of the operator to control vehicle motion in by-wire implementations include the overall range of motion (throw) of the HMI, the relationship of angular displacements specified through the device and the response of the vehicle, and modifications of this relationship because of vehicle motion characteristics (speed, lateral acceleration). Variations in driver-vehicle performance are a consequence of dynamic characteristics of the

operator, the vehicle, and most importantly, their interaction. If nothing else, this review has clearly depicted the shaping function as a central component of influence over system performance. Moreover, it is apparent that no single shaping function will suffice across all driving scenarios. For instance, as the basis of an nVGR system, a shaping function that is constant across vehicle speed is unlikely to be as robust as one that has sVGR characteristics. Figure 6 provides an example of how both speed and input angle could be accounted for with a dynamic shaping function, effectively inte-grating nVGR with sVGR characteristics (Andonian et al., 2003). Based on the current review, it appears as if the ideal shaping function would not only vary according to HMI input angle and vehicle speed but would also adapt appropriately to lateral/yaw accelerations as well as the task for which the current vehicle is being used.

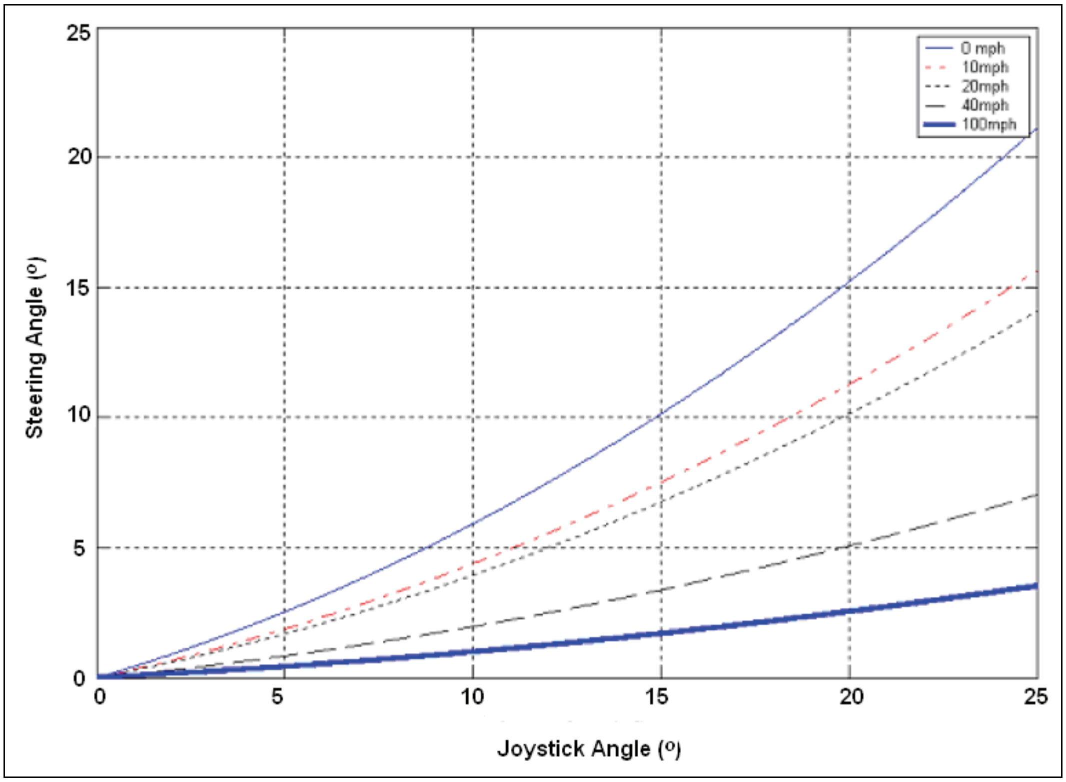

Figure 6. Joystick sensitivity as a function of joystick angle and simulated speed. (Image adapted from Andonian et al., 2003, figure 6, p. 5.)

8. Conclusions and Future Directions

To date, vehicle control characteristics and how they impact operator performance in secure mobile operations remain a primary focus of the collaborative program at TARDEC and ARL. Thus far, a small number of well-controlled studies have begun to disentangle the web of issues underlying the optimization of driver-vehicle performance for military tasks. Early efforts

identified minimum linear steering ratios during certain high-speed tasks such as lane keeping and during a double lane change (McDowell, Paul, & Alban, 2007). Careful design decisions are needed since driver performance remains compromised at higher vehicle speeds and when nonstandard HMI devices, such as joysticks, are implemented. The results of the experimental studies that have been completed thus far are providing important information specific enough to facilitate the establishment of design guidelines for intelligent military vehicles. Further research is needed to extend the current understanding so as to establish how steering control must be varied through an adequately defined shaping function to identify solutions for performance issues that persist beyond those that can be addressed through the shaping function.

However, understanding shaping function solutions will not, on its own, be sufficient in our goal of improving and optimizing driver performance. A number of other important areas of by-wire systems and human performance continue to justify examination. In particular, research needs to build toward increasingly sophisticated solutions to the problems of vehicle control that incorporate many of the technologies that have fostered advancements within the civilian automotive industry. Four areas for future research that we have identified as particularly relevant include

- Assessing the utility of force feedback to the operator through the HMI in order to facilitate a "natural steering feel" as if the vehicle were actuated through mechanical linkages;
- Determining an appropriate means for compensating the lag in information flow between driver input at the HMI and feedback regarding vehicle motion, for example, inclusion of augmented visual displays that indicate predicted vehicle motion based on current state and input;
- Determining a means for compensating biodynamic feedthrough to minimize unintended steering inputs, for example, incorporation of sensors measuring physical displacements of the operator and subtracting from the command input those elements attributable to vehicle-induced motion;
- Facilitating ease of operator interaction with an ergonomic work station while decreasing physical and cognitive workload.

Although dramatic strides are being made through research in automotive technology, advanced telerobotics, and autonomous control systems, the continued integration of these advancements with military applications presents challenges that are yet to have any clear solution. Despite the need for continued research and development, observations of current by-wire implementations within military test bed vehicles remain encouraging and the clear potential for future functionality in secure mobile operations becomes increasingly apparent with each insight gained through careful experimentation.

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